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RESEARCH IN FOUNDATION GROUTING WITH CEMENT

MISCELLANEOUS PAPER NO. 6-384

March 1960

U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS
Vicksburg, Mississippi

ARMY-MRC VICKSBURG, MISS.

RESEARCH IN FOUNDATION GROUTING WITH CEMENT

By Thomas B. Kennedy

SUMMARY

Numerous investigations involving cement grouting of foundations have been conducted since the first large-scale grouting attempt in 1910. Modified cements, mixtures of cement and additives or replacement materials, and proper proportioning of grout ingredients have been developed for various projects as needed. Since the grouting requirements of each job differ, no all-purpose grout or grouting method has been established. However, results of the laboratory and field tests described in this paper show the advantages and disadvantages of cement grout incorporating admixtures, of varying water-cement ratios, and of varying grading and fineness of grout ingredients. In addition, grouting techniques, grouting pressures, and types of equipment utilized in these tests are described.

Suggestions for future research in cement grouting from engineers experienced in this field included investigations for:

1. Controlling the setting time of cement slurries and cement mixtures.
2. Tracing grout in pervious formations.
3. Improving mixer and other equipment efficiency.
4. Grouting fine fissures.
5. Studying the characteristics of grout incorporating new replacement materials or additives.
6. Exploring more thoroughly the foundations to be grouted.

RESEARCH IN FOUNDATION GROUTING WITH CEMENT

By

Thomas B. Kennedy*

PART I: INTRODUCTION

Foundation grouting is used primarily in the treatment of rock formations and, to a lesser extent, for soil, sand, or sand and gravel formations. The over-all plan for a grout treatment is governed by the requirements of the particular structure; however, the primary requisite for any treatment is that the grout mortar readily and solidly fill the areas to be grouted and permanently retain its original volume. Standard grouting techniques often must be modified to meet existing conditions, and selection of proper materials, equipment, pressures, and techniques, as well as close control of proportioning of the ingredients of the grout, determine the success of a grouting job. Of course, a thorough knowledge of the foundation characteristics is a prerequisite to intelligent design of a grout treatment.

As a result of the diversity of problems that have been encountered in grouting work, numerous materials, mixes, techniques, and equipment have been developed. This paper presents a review of the literature relating to these developments.

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PART II: RESEARCH IN CONJUNCTION WITH SPECIFIC CONSTRUCTION PROJECTS

Early Investigations at Estacada Dam

The large-scale treatment of a foundation by grouting was first attempted in 1910 in the cutoff for the Estacada Dam.[1*] The job required much experimenting, and although the grouting was considered unsuccessful, considerable knowledge was gained from the experience; it may be summed up as follows:

1. All drilling, testing, and grouting should be done through casings set in the concrete cutoff.
2. All testing should be performed from elevated tanks and not by pump.
3. Each hole should be tested and grouted as soon as drilled, then the drills kept away from the probable zone of diffusion for a few days.
4. In grouting, especially at high pressures, it is best to close the valve before the tank is entirely empty to prevent the air from following the grout into the hole.
5. A comparatively thin mixture should be used to begin grouting and, if taken freely, thickened until each succeeding batch requires either an increased discharge time or increased pressure. The forcing of charge after charge of thin grout into a hole probably is a waste of cement.

The experience at Estacada indicated that grouting should not be relied on in lieu of the usual concrete cutoff, for two reasons:

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* Raised numbers refer to similarly numbered references at the end of the text.

1. The efficiency of grout as a curtain wall cannot be predicted.
2. The proper diffusion of the grout can be secured only when the concrete of the cutoff closes the surface seams and confines the pressure to a depth at which it may be effective in tightening the underlying material.

Investigations at Hoover Dam

Initial work

In an article published in ACI Proceedings in 1933, Steele[2] outlined a program of investigations to obtain information for use in contraction-joint grouting at Hoover Dam. A review of contraction-joint grouting experiments was also included. The investigations were conducted in the Denver laboratories of the Bureau of Reclamation and involved experiments with fineness of the cement, water-cement ratio of the grout, width of contraction-joint opening, grout pressure within the joint, and shearing strength of the grout film. For the investigations, a split cylinder of mass concrete, 5 ft in diameter and 7 ft high, cast to simulate a contraction joint in a dam, was so constructed that the thickness of grout film could be easily and accurately controlled. Although the laboratory tests were concerned with contraction-joint grouting, the following results are also pertinent to foundation grouting:

1. To obtain satisfactory flow in grouting a contraction joint, the cement should be passed through a 200-mesh sieve immediately before the grout is mixed.
2. For cracks of the order of 0.05 in., a grout in which the ratio of water to cement is 0.75 by volume gives the most desirable

film. A water-cement ratio of 1.00 contains too much free water that cannot be forced into the concrete or otherwise dissipated.

3. Joint pressure of 90 per cent efficiency and joint coverage of 99 per cent are easily obtained with a grout having a water-cement ratio of 0.75, and with a film thickness of the order of 0.035 in.

4. Shear tests on grout films fog-cured at 70 F for 28 days demonstrated that increasing the pressure within the joint immediately after it is filled does not appreciably increase the shearing value of grout films of equal initial water-cement ratio.

5. With an apparatus used for determining punching shear, an average shearing value at 28 days age of films fog-cured at 70 F was 900 psi.

Hoover Dam (formerly Boulder Dam) was completed in 1936 and, on the basis of a great deal of experience obtained at this project, Minear and Jones[3,4] reported certain conclusions as to the best materials, equipment, and procedure for grouting projects of a similar nature. Some of these are as follows:

1. Grout should be injected by pumping and not by compressed air. Mixers should be provided with meters for controlling the amount of mixing water. (Grout equipment developed for this project consisted of a grout mixer, a mechanically agitated pump, and two high-pressure sludge pumps.)

2. The water-cement ratio, pressure, and rate of pumping should be coordinated by "feeling out" the hole to be grouted.
3. Pumping speed should be controlled by manipulation of the water-cement ratio. When the speed falls below normal, the water-cement ratio should be increased proportionately and vice versa.
4. Neat portland-cement grout is probably the best all-purpose grout and was used almost exclusively on the Hoover (Boulder) project since a sanded mixture proved undesirable because of its effect on the pumps as well as the difficulty of holding the sand in suspension.
5. While the use of extra finely ground cement is essential in contraction-joint grouting, it is of secondary importance in rock grouting.

Use of special cements and additives

Additional grouting at Hoover Dam during the period from 1938 to 1947 required further investigation of grout mixtures and techniques. Simonds and Boggess[5] discussed this program of construction which included the grouting of foundations and abutments, and extension of the drainage system. During the initial filling of the reservoir, particularly in 1937 and 1938, excessive seepage into the penstock tunnels developed and water from the foundation system entered the galleries of the dam in excessive quantities at certain localities. Large flows of cold water were discharged from several drains, and hot alkaline water dripped through cracks in the concrete lining of some of the penstock tunnels and damaged the paint and metal work. The uplift pressure on the base of the dam had increased by 1937 to undesirable magnitudes in certain areas. Consequently, the purposes of the additional grouting were to reduce this uplift pressure and seepage through the abutments. The grouting treatment described in the following paragraphs proved successful for these purposes.

The use of special cements for grouting the cracks leaking the hot alkaline waters, which occurred in warm spring areas, was investigated. Flash sets occurred with portland cement, and the grout pumps would stall so that no grout was forced into the foundation as the pumping pressure built up. It was theorized that the flash sets were due to the high temperature of the alkaline water, the insufficient flushing of grout holes with cold water before the grouting began, or the contact of the cement with the alkaline waters. The first special cement tried was an oil-well-type grouting cement which had been used successfully to grout areas in which hot salt water had been encountered. The oil-well cement was found to possess some desirable characteristics for grouting but was not completely satisfactory because it contained some unground clinker ("spitzers") which had a tendency to settle out when thin mixes were used. Several cements were also tried during the program of additional grouting but did not give satisfactory results. Fly ash was tried with modified cement but produced no material advantage. At that time, the staff of the Concrete Laboratory in the Chief Engineer's office had been experimenting with modified cements and retarders in an effort to duplicate the characteristics of the oil-well cement. It was found that the addition of small amounts of a commercial retarder to modified (similar to present type II) cement resulted in a product that had characteristics similar to oil-well cement and was more finely ground. The retarder was composed of 87-1/2 per cent calcium salt of lignin sulphonic acid and 12-1/2 per cent triethanolamine. Experiments with the retarder at Hoover Dam produced beneficial results in the grouting. It was mixed into a 12-1/2 per cent solution and added to the mixing water of each batch in the proportion of one pound of retarder to six sacks of modified cement. Field tests indicated that it was possible to inject more cement into the foundation by using modified cement with retarder than by using either oil-well cement or modified cement without retarder. Retarder was used with modified cement in the grouting until May 1944 when the grouting had reached the areas of cold ground water and the retarder was not needed.

Effect of water-cement ratio

Experience had shown that grout having a water-cement ratio less than 3:1 by volume could not be injected at pressures greater than 450 psi without risking the plugging of the hole being grouted. Thinner grout mixes were more successful for squeezing off seepage through the andesitic foundation rock. At the beginning of the program of additional grouting, the water-cement ratio of the grout mix varied from 7:1 to 3:1 by volume. Thinner grout mixes were used more frequently as the work progressed; the most generally used ratios varied from 10:1 to 4:1. In fairly tight water-bearing rock, many holes were grouted with mixes having water-cement ratios of 20:1, 14:1, and 12:1, and unless surface leaks developed, grout thicker than 7:1 was rarely used. Thin mixes injected at pressures of 500 psi or slightly greater formed excellent grout films.

Grouting procedure

A systematic procedure of stage grouting was used at Hoover Dam. In areas where open seams were crossed, as determined by the flow of water into the hole, it was customary to drill slightly beyond the seam and then grout it. After the grout had set for 16 hours, the hardened grout was drilled from the hole. The condition of the grout determined the type of bit to be used in cleaning out the hole. To save the diamond bits whenever possible, "stoodite" saw-toothed bits were used. In holes where flows of water of 200 to 400 gallons per minute were encountered, a satisfactory, cup, washer-type packer and a method for inserting it against large flows of water were developed. In areas where warm water was encountered, injection of fairly large quantities of cold water into the grout holes for several hours before the start of grouting was found to be beneficial in retarding the time of set of the cement in the grout.

Studies of Grout Mixtures at Chief Joseph Dam

In January 1950, Wells[6] described an experimental grouting investigation for Chief Joseph Dam, in which a method of grouting for the control of seepage into the excavation areas of the right abutment was studied. The program involved development of: (1) a grouting mixture capable of penetrating the materials of the pervious formation, (2) an economical method of drilling a large number of holes in the gravel, (3) a procedure for introducing the grout mixture into the pervious material; and the determination of the efficacy of the grouting. Both laboratory and field studies were made.

Information on the formation of the right abutment materials prior to the grouting experiment raised a question as to whether cement grout would have the necessary penetrating qualities. Accordingly, several grout mixtures using bentonite, silt, plaster of Paris, asphalt emulsion, etc. were developed in the laboratory.

Field experience

In the initial field trials, the portland-cement grout appeared to be penetrating the formation at Chief Joseph Dam successfully, consequently it was used in the grouting program rather than the grout mixes with the other materials mentioned.

Several weeks were spent in attempts to jet pipes into the gravel formation but all attempts failed. A heavy churn drill rig was finally used successfully but progress was limited to about 10 ft per shift. The use of a well-graded sandy gravel (-3/4 in.) for back-filling drill holes around the grout pipes was very effective in preventing grout from flowing up the outside of the grout pipe casing.

A test pit was excavated in the grouted area and showed that the gravel was well sealed and effectively grouted from a depth of 23 ft to 52 ft where bedrock was encountered. Areas of excessive leakage occurred in the upper zone where very little attempt had been made to grout and at bedrock where cracks and fissures were not sealed. The following was considered an effective grouting procedure: (1) grouting from bedrock up using 5-ft stages, (2) alternating between grout holes, and (3) using an initial mix of one part cement to five parts water with gradual thickening until a pressure of 150 psi was obtained. A grout-hole spacing of 7.5 ft produced an effective seal and results indicated that a greater spacing could be used. However, because of the excessive estimated cost for a grout curtain, the grouting scheme was abandoned in favor of an alternate plan providing for seepage control.

Foundation Grouting at the Savannah River Project

In 1952 Johnson[7] reported on foundation grouting operations at the Savannah River Plant of the Atomic Energy Commission. The Atomic Energy Commission, the Du Pont Company, and the Corps of Engineers had collaborated in the geological and foundation exploration program for the Savannah River Plant and after careful study of the geological report it was concluded that foundation conditions were, in some respects, unusual and that grouting would be required beneath some of the structures.

The presence of sinks, due to solution of calcareous materials, throughout the plant area caused considerable concern for the foundation stability, and a foundation-grouting program was proposed. A limited number of laboratory tests were made at the Waterways Experiment Station, Corps of Engineers, to determine the most suitable grout mixtures. Then a small-scale grouting test was made at the plant site to determine if the grout mixture proposed for use could be pumped satisfactorily or would segregate excessively. The test indicated that the foundation would take freely the grout pumped into it. The foundation soils at the plant site consisted of sands and mixtures of clay and sand. Under normal circumstances, soils of these types cannot be grouted, even with a grout consisting of cement and water, and would never be considered capable of receiving a grout consisting of sand, cement, and water. But the highly unusual condition, i.e., solution of the calcareous material in the zone beneath the plant, made it possible and necessary to grout. The grouting program accomplished the objectives desired and, in general, worked out as anticipated, although considerably more grouting was required than had been expected. The various grout mixtures tested in the laboratory, including the mixture used, are described in the following paragraphs.

In the laboratory, various proposed grout mixtures were tested for tendency toward segregation and general workability of the mix. A few unconfined compression tests were performed to determine if the samples had adequate strength. It was considered unnecessary for the grout to have great strength, or that its rigidity should greatly exceed that of the natural ground.

Trial batches of grout were prepared using 8 cu ft of sand, 25 lb of bentonite, cement varying from 1 to 1-1/2 bags per batch, and water varying from 4 to 10 cu ft per batch. Other test batches were made up using the same proportions but substituting 1-1/2 cu ft of fly ash plus 2-1/2 lb of a water-reducing, expansive admixture for the bentonite. Tests indicated that the mix consisting of the 8 cu ft of sand, 1 cu ft of cement, 25 lb of bentonite, and 8 cu ft of water appeared satisfactory and it was used for the initial field tests. However, it was discovered that this mix set up too slowly, was weaker than considered desirable, and was too soft for testing the day after placing. A more suitable mix was obtained by increasing the portland cement to 1-1/2 cu ft and decreasing the water from 8 to 6 cu ft. The mixes consisting of sand, cement, admixture, and fly ash did not appear to possess any advantages over the latter sand-cement-bentonite grout. Therefore, after consideration of the availability of materials and cost, it was decided to use the sand-cement-bentonite grout in the field-grouting operations.

Other laboratory tests consisted of substituting slag cement for 50 per cent of the portland cement in the standard mix and determining unconfined compressive strength on the resulting mixes. These mixes showed a tendency for a lower compressive strength at the early ages, but after 7 days, the strength was equal to or higher than that of the standard mix containing all portland cement.

Two series of tests were made with aluminum powder added to the grout mixture. In the first series, 4 g of aluminum powder was added to a batch of grout, and in the second series, 8 g was added. Compression tests revealed that the strength was not affected to any significant degree by the addition of aluminum powder. Tests were also made of the aluminum-powder mix to determine shrinkage and expansion characteristics. After 24 hours the plain grout had contracted 2.3 per cent of its original volume (980 cc) and the aluminum-powder grout had expanded 4.3 per cent and further expansion was indicated. The addition of the aluminum powder had no significant effect on segregation.

Unconfined compression tests were made with sawdust added to the normal grout mix in the proportions of 3, 5, 8, and 10 per cent by weight. The sawdust was coarse pine material, air-dried, and was mixed with the grout as it came from the field mixers. The compressive strengths of the sawdust mixes were substantially lower than those of the standard grout mixes. However, a comparison of test data using the relation previously established between strength and water content indicated that the results of tests with sawdust mixes agreed with those of the plain grout for comparable water contents.

Use of Rock Flour at Norris Dam

In describing the foundation treatment of Norris Dam during the construction period of 1933 to 1936, Lewis[8] reported the results of some laboratory grout tests supplemented by additional investigations in the field. Preliminary field tests were made to determine the suitability of rock-flour mixtures for grouting. The results indicated that grout consisting of equal parts of cement and rock flour and a water-cement ratio of 1.0 was more desirable than plain cement grout because it penetrated the cracks better and did not set up in the pipeline during pumping. The rock flour was finer than the cement and definitely had a retarding effect upon time of set of the mixture. However, the use of a slow setting material such as rock flour increased the distance traveled by the grout fluid so that areas completely outside of the region that needed treatment were grouted and the quantity of material used was increased appreciably. In order to reduce unnecessary consumption of material, tests were made to determine the effect on setting time of adding calcium chloride ($CaCl_2$) to the grout. The acceleration of set caused by the addition of 3 per cent $CaCl_2$ by weight of the cement to a marked extent counteracted the retardation caused by the rock flour. The resulting product possessed pumping and handling characteristics similar to those of regular portland-cement grout. Compressive tests on specimens removed from the mixer in the field showed that the product was sufficiently strong and would be able to resist erosion. Specimens cored from grout-filled seams after the rim grouting was under way exhibited a compressive strength of 2000 psi at approximately 45 days.

The rock flour used in these mixes contained a quantity of fine clay lumps that failed to disintegrate in the course of mixing. After some experimenting, it was found that a satisfactory method of breaking down these lumps was by use of a separate, mechanically agitated mixer from which the rock flour passed as a slurry through a screen to the grout mixer. The rock-flour mixer was similar to that used for the grout and was driven by the same type of air motor, but had one compartment instead of two.

During the preliminary grouting for sealing the first cofferdam, an attempt was made to economize by mixing sand with the grout. The experiment was unsuccessful as the pump and lines were plugged solid. Cores of the sand grout later removed from nearby holes showed a tendency toward segregation; the material was lean and crumbly and generally of poor quality. Lewis stated that he felt it would be unwise to attempt the use of sand for grouting seams in a foundation that would be subjected to more than a very moderate head.

Cement Grout with Asphalt Emulsion

As a result of a cooperative research and field testing program undertaken in 1941 by the Texas Company and the Atchison, Topeka, and Santa Fe Railway, and reported in 1946 by Thurston,[9] it was discovered that in roadbed stabilization the addition of emulsified asphalt to the grouting mixture improved its penetrating and sealing properties and permitted the use of grout mixtures containing less portland cement. The standard emulsified asphalt originally used set too slowly, and a quicker-setting emulsion was developed by adding small a ounts of chemicals to facilitate mixing with the cement and sand, to control the setting time, and to minimize the amount of foaming and settlement. This emulsion was most successful in improving stabilization, lowering costs, and expediting grouting work.

Grout containing the quick-setting asphalt can be injected by either pneumatic or hydraulic pressure. Both methods have their advantages and both have been used successfully. Soil conditions determine the correct grouting mixture to be used. The following recommended limits allow leeway for all types of conditions:

Mixture	Parts by Weight	Parts by Volume
Portland cement	1	
Sand	6-20	
Emulsified asphalt per cu ft of sand		0.1 to 1.0 gal
Water per cu ft of dry mix		4.5 to 8 gal

A very fine "blow" sand was found to be the most suitable for the grout mixture. Such a sand, of which about 90 per cent will pass through a 48-mesh sieve and about 20 per cent through a 100-mesh sieve, pumps most easily, causes the least wear on the pumping equipment, and flows most readily into the voids. When sand is not ideally graded in particle sizes, the addition of fly ash at the rate of 3 to 12 lb per cu ft of other dry materials improves pumpability.

Grouting Lignite Seams at Garrison Dam

Experimental grout studies[10] were conducted in July 1948 on the lignite seams in the Fort Union formation at Garrison Dam. The tests were made in the powerhouse area as it was considered the most suitable for subsequent excavation to observe and study the effectiveness of the grout pattern. To determine the feasibility of grouting the lignites, the following problems were explored:

1. Methods of grouting.

2. Grouting pressures.

3. Water-cement ratios.

4. The most effective and economical quantity of grout for each hole.

5. Spacing of holes.

6. Size of holes.

The packer used for most of the tests seems to have been unusual. It was developed from soft rubber hose, had an outside diameter of 3-1/4 in. and an inside diameter of 2-1/4 in., and was cut in lengths of about 2-1/2 ft for these particular tests. The packer was assembled onto a packer coupling end; the upper coupling was movable to allow the packer to expand against the bore of the hole without exerting an undue strain on the packer material at the coupling. Metal straps were used to fasten the packer to the couplings; however, it was necessary to place tape under the straps to prevent cutting of the rubber by the straps. The expansion of the packer against the sides of the hole in the soft Fort Union formation was best obtained and maintained through the use of water instead of air as the expanding force.

The following pertinent conclusions were derived from the tests:

1. The 4- and 7.5-ft-thick lignite beds in the powerhouse area of the west abutment of Garrison Dam can readily be grouted.

2. These lignite beds can be grouted at one time or separately.

3. Either the "full-depth" or "stop" method of grouting was satisfactory.

4. Water-cement ratios ranging from an initial 1.5 to 1 to 0.7 to 1 appeared to be the most satisfactory in the test area.

5. The rubber packer performed satisfactorily with water pressure used as the expanding force.

6. A pressure differential of 25 psi on the packer was satisfactory.

The grouted lignites were examined in excavations made for the purpose of studying the joint patterns and the success of the grouting.[11] The examinations indicated that:

1. Both the 4- and 7.5-ft-thick lignites were readily grouted and it was assumed that other lignites in the same area could also be successfully grouted.

2. The stop method, instead of the full-depth method, should be used in grouting the lignites in this area because there was almost no grout in the 4-ft-thick bed where the full-depth method had been used.

3. The use of a packer made it possible to obtain more accurate information on the horizon to be grouted and to accomplish better washing of the bed during pressure-testing.

4. A spacing of 20 ft would prove satisfactory in obtaining an overlap grout pattern, provided the stop method of grouting is used.

5. Horizontal bedding planes or joints serve as grout channels. The pattern and continuity between the vertical and horizontal joints were excellent.

6. On the basis of the number of joints observed per unit area on the surface of the two lignites, the percentage of voids was calculated as approximately 0.8 per cent. Prior to and during the testing program, it was assumed that the percentage of voids in the lignites was 0.5 per cent.

7. The relative ease with which these lignites were test-grouted indicated that high pressures and thin grout mixes would obviously be inapplicable and would result in an uneconomical use of grout by forcing it long distances on each side of the curtain.

Grout for Stabilizing Soft Soils, San Francisco Bay

An investigation[12] concerned with the feasibility of mixing portland-cement grout in place with soft soils to form a stable mass was conducted by Intrusion-Prepakt, Inc., under the direction of the U. S. Naval Civil Engineering Research and Evaluation Laboratory. The research included both laboratory and field studies of methods of mixing with special emphasis on their applicability to naval construction, particularly in water-front foundation problems. In the laboratory tests, wooden boxes were filled with various soft soils, and various mixing heads were used in grouting the soils. When the soil in a box had been grouted and attained its set, the box sides were removed for examination and sampling of the soil. Grouting materials used were standard portland cement type I, fly ash, a water-reducing, expanding grouting aid, uniform clean sand, and water. To provide a measure of the effectiveness of the grouting, the following control tests were performed on the grouted soil: (1) strength (including compression cubes and tensile briquets), (2) composition, and (3) miscellaneous such as determination of soil properties. Grout-line pressure measurements were also made.

The field tests were performed in natural mud deposits at San Francisco Naval Shipyard, Hunters Point, on the west side of San Francisco Bay. The method consisted primarily of mixing grout into the soil by pum while the soil was in place. This was accomplished by employing an auger or mixing blade with grout outlet ports in the lower end, and with hol shaft. As the auger advanced into the soil, a controlled quantity of grout was pumped through the hollow shaft and distributed through the outlet ports. Thus a column of grouted earth was created. A light core-drill apparatus, with a blade-type mixing head substituted for the usual bit, was used to accomplish the work.

It was concluded from the study that the process of mixing grout in place with soft soils to form structural elements (such as piles) is feasible within limits, but is more adaptable to repair jobs and small-scale construction than to large permanent works. By exercising proper control over mixing procedures, grout type and quantity, and by making shallow trial units, a "pile" of satisfactorily uniform cross section can be produced to a depth of at least 40 ft in very soft soils. The depth is limited by the power of the equipment available and by the soil which must have very low shear strength and be saturated. Specific conclusions derived from the investigation were:

1. The uniformity of grouting depended largely upon quantity of grout introduced, type of mixing head used, and the number of head revolutions per lineal foot. Usually the center portion of the unit was richer in grout than the outside portion and the grout did not permeate appreciably beyond the diameter of the mixing head.
2. The strength of the field mixes was erratic and could not be predicted accurately from laboratory mixes using the same quantities of the same materials.

3. It did not appear feasible to use less than 35 per cent grout in the field mixes and the tensile strengths of the soil-grout mixes were very low.
4. The grouts containing fly ash and the grouting admixture offered advantages over neat-cement grouts from the standpoint of strength and pumpability.
5. The most suitable mixing head for placing soil grout units was found to be the individual blade type as contrasted with the continuous auger type. Advantages of this method of grouting are the low overhead clearance required for placing and the relatively light equipment used in the operation as compared with conventional pile-driving equipment.

Grout for Mixed-in-Place Piling

E. R. Colle[12A] reported an investigation undertaken for the Department of Forests and Water Division of Flood Control, Commonwealth of Pennsylvania to determine the feasibility of using piling formed by mixing grout in place by use of an auger with the soil, sand, and gravel on the river side of the concrete floodwall of the Lackawanna River at Scranton, Pennsylvania, to stabilize and protect the wall.

Six 20-in. diameter test piling 16 ft long into the underlying silt and sand were made in groups of three each so spaced as to overlap each other. The presence of boulders to a depth of seven to nine feet made it necessary to excavate the test area to that depth and back-fill with river bed material from near the site. In the first group of three the grout proportions were 3 bags of cement, 1 bag of mineral filler, 1 per cent chemical aid by weight of cement and 17 gal of water. In the second group of three the proportions were 2 cement to 1 filler plus 1 per cent aid and 15 gal of water. Thirty, 40, and 50 per cent grout was used in piles 1, 2, and 3, repeated in piles 4, 5, and 6, respectively.

After 28 days diamond cores were removed from the test piling drilled into the portion of each piling made from the grout mixed with the silt underlying the backfilled area. Strengths ranged from about 700 to 1650 psi. Fifty per cent grout was required to produce the higher strengths. Although the desired compressive strengths of 2500 and 3000 psi were not obtained, it was the opinion of the reporting engineer that higher strength than that indicated could be realized by allowing for the overlapping of the piling and using larger diameter than the 4.8-in. cores tested. It was the Colle's opinion that a mixed-in-place pile wall was a practical application for insuring stability of the floodwall and prevent loss of foundation material from under it.

Grout for Mixed-in-Place Cutoff Wall

Another investigation was reported by Colle[12B] made for the purpose of determining whether or not the mixed-in-place pile technique could be used to form an impervious core wall in proposed levee construction for flood control in Stroudsburg and East Stroudsburg, Pennsylvania.

Six laboratory mixtures gave promise of fulfilling the requirements of satisfactory cutoff. The parts by weight of the basic grout for three mixtures 1 cement:0.4 mineral filler:0.28 bentonite:1.78 water:0.0141 chemical aid.

The parts by weight for the basic grout for the other three mixtures contained no bentonite and was as follows: 1 cement:0.39 mineral filler:0.57 water:0.0139 chemical aid. Each grout mixture was then mixed with 30, 40, and 50 per cent soil by volume from the test project site and small cylinders and beams were made for compressive and flexural strength, deflection, modulus of elasticity, permeability, and setting time. Little difference was noted in the deflection at rupture between the specimens with and without bentonite. Permeability of specimens with both grouts approached that of conventional concrete. Strength of the bentonite-grout specimens, 330-500 psi at 28 days, was considerably less than the neat-grout specimens 3530-4600 psi, but since flexibility and watertightness were considered more important than strength it was decided to try the cheaper grout containing 20 per cent bentonite for the mixed-in-place test piles to form the impervious core wall as well as the grout without bentonite. Five piles with 20 per cent bentonite and eight without were made. Two piles apart from each other contained bentonite, one apart from the others was without bentonite. Three piles were made on 14-in. centers with bentonite, two on 14-in. centers without bentonite, and five on 12-in. centers without bentonite. All piles were 15 in. in diameter.

Difficulty was experienced in attempting to extract cores from the test piles because of the oversized pebbles in the piles and because of the tendency of the grout with bentonite to crumble. The strength of the cores without bentonite at 29 days age was 1600-1800 psi and with bentonite 150-180 psi.

The recommendation of the engineer was to use grout with 20 per cent bentonite and to excavate along the line of the cutoff to remove troublesome boulders and backfill prior to making the cutoff with material with top size not exceeding 4 in.

Use of Lumnite Cement

An informational folder[13] entitled Lumnite, issued in 1950, listed many uses and characteristics of calcium-aluminate cement which might prove of value in some phases of grouting. The booklet does not treat of research, but it does contain information that might be found useful for special grouting conditions; therefore, is described here. Aluminous cement sets and hardens when mixed with water and can be subjected to the full load for which it is designed in less than 24 hours after placing. Some of the pertinent special uses of aluminous cement are:

1. For grouting leaks where quick-hardening properties are highly advantageous, such as in work around dams, mines, and tunnels.
2. In industrial grouting, such as setting bed plates for heavy machinery and equipment.
3. In quick-setting gunite mixtures.

When portland cement is mixed with aluminous cement, the set is greatly accelerated, frequently causing flash set. Such mixtures are not recommended for ordinary construction work, but when placed with a cement gun the aluminous cement-portland cement mixtures may solve difficult construction problems. In the cement gun, the water joins the cement at the nozzle of the gun. Thus, flash-setting mixtures may be used since the pneumatically-placed mortar is in place before setting can occur. This method is convenient for special conditions, such as shutting off water, sealing caissons, and stopping seepage in rock seams.

Other Reviews of Grouting

A thorough review of equipment, materials, and procedures used in foundation treatment is presented by Simonds, Lippold, and Keim[14] in a publication dated February 1950. The information contained in this paper is based, for the most part, on experiences gained in grouting the foundations of 20 or more large dams. It is concerned with the application of neat-cement grout, although the use of other foundation grouting materials, such as asphalt, bentonite, and clay, is also discussed.

In an article published in October 1955, Clark[15] assembled the fundamental principles involved in grout penetration. Although no new research of cement grouting is described, many conclusions are listed.

Use of Injection Devices and Ultrafine Cement at Shaver Dam

During the years 1945, 1947, and 1949, the Southern California Edison Co., Los Angeles, Calif., conducted experimental programs in grouting leaking construction joints at the company's Shaver Dam. A specially developed cement and equipment furnished by the Portland Cement Association were used in the work. Grouting successfully stopped some of the leakage but water was still emitted by some of the very fine cracks. Three methods of grouting, none of which was entirely successful, were tried in the experimental program.

1. The hand-thrust method was tried in which gun seats anchored astride the injection holes in the leaking construction joints, and a rubber-tipped grout injection gun were used. In this method the heavy pressure required to obtain penetration made it difficult to maintain contact between the gun seats and the guns.

2. Holes were drilled in the construction joints and expansion shields were placed in the holes. A specially made pipe connected the hole with the pump. Fines produced by the drilling could not be removed completely; consequently, the cracks were bridged, causing grout refusal.

3. A new injection device was used which proved to be the most successful of the three methods of grouting tried. The device consisted of a rubber-gasket-sealed plate with a hole in the center over which a 3/8-in. pipe nipple was welded. The plate was clamped over the injection hole by bolts inserted through the plate into lead expansion shields placed in the dam face.

Grout used in this program was prepared from 0-40 micron fraction of high-early-strength portland cement. It was found that a grout mix of 4.0 to 5.0 water-cement ratio was required to penetrate some joints.

The High-Speed, Dual-Drum, Circulating-Type Mixer

In February 1955, a report[16] on the use of a high-speed, dual-drum, circulating-type grout mixer at Folsom Dam was issued by the Sacramento District, Corps of Engineers. The machine is intended principally for mixing mortar grout and is claimed to produce a more stable, fluid grout than the regular-speed paddle-type mixer. Comparative tests made with this mixer and a standard paddle-type mixer indicated that mixing substantially equal could be produced by conventional mixers and methods if the normal mixing time is increased sufficiently.

The advantages of the high-speed mixer were summarized as follows:

1. Better mixing of the grout and greater freedom from lumps are achieved.

2. Mixer can be at ground level. Cement can be taken directly from back of truck with less lifting and handling.

3. Discharge can be pumped to some distance from and a little above the mixer by its pump.

4. The apparatus is highly mobile, compact, and flexible.

5. It is very easy to clean.

6. The mixer mixes small batches, and is therefore better adapted to sensitive control of water-cement ratio.

The following disadvantages of the high-speed mixer were reported:

1. Heats grout or water left in running mixer.

2. Is more expensive to buy and to maintain than conventional mixers.

3. Requires a little more care in operation than a conventional mixer, particularly in fast operation.

PART III: LABORATORY RESEARCH IN USA

Bureau of Reclamation

Laboratory research in grouting performed by the Bureau of Reclamation was summarized from their reports[17-26].

The Bureau of Reclamation has done a considerable amount of investigation in the development and use of suitable instrumentation to measure fluidity, flowability, or consistency of grouts. Instruments that have been tried are the Standard Oil Company's oil well testing apparatus, a piano-wire torque meter, an inclined pipe flow meter, shot-cell flow meter, a glass tube and funnel viscosimeter, and the Stormer viscosimeter. Some grouts can be measured well in one type of apparatus but not in another. Sanded grouts, for example, might not be readily measured in some sorts of viscosimeters, and the torque meter might be found not sensitive enough to measure slight changes in viscosity of very thin neat grouts.

The oil well testing apparatus measured viscosity and mixing time by use of a complicated procedure not suitable to ordinary grouting needs.

In attempting to obtain equipment suitable for measuring the consistency of grout, the Bureau of Reclamation built a device, called a torque meter, based on design and plans from Raymond E. Davis[17]. The torque meter was a device wherein a turntable on which a pan of grout 2 in. deep and 7 in. in diameter revolved. A pendulum weight in form of a disc weighing about 23 lb with two crossed 1/8-in. round rods attached to the underneath was suspended from a 35-1/2-in. length of No. 18 music wire above the revolving pan. The disc weight was graduated from 0 to 360 degrees. Provision was made for lowering the crossed rods attached to the disc into the revolving [illegible] grout. The moving grout imparted torque to the suspended assembly. The thicker the consistency the greater the torque reading.

Tests to develop further equipment to measure flowability were made[18] where the length of time was observed required to discharge a fixed volume under low head (16 in.) through a 7-ft length of 1/2-in. pipe inclined upward at 32°. This approach was not too successful and led to studies to develop the shot cell and the glass tube viscosimeter[19].

In development of the shot cell it was desired to obtain apparatus sensitive enough to detect small changes in the flowability or ability of thin grout to penetrate restricted openings or penetrate a bed of granular materials. The cell consisted of a transparent plastic tube containing a known weight of steel shot. The length of time required for a known quantity of grout to pass through the cell at a carefully controlled constant pressure provided a quantitative measurement of the flowability.

Tests of grout through the cell and through a viscosimeter made of small diameter glass tubing with a constricted area caused by drawing in a laboratory burner flame indicated that flowability and viscosity are closely related. Both were found to be suitable to indicate small differences in the flow characteristics of cement-water slurries. The Stormer viscosimeter, a piece of commercial equipment, was found to be very suitable for measuring the viscosity (consistency) of neat grouts[25].

The Bureau has conducted considerable research into the effects on the properties of grouts of adding organic materials and mineral fillers to grouts. The effects of passing cement through a colloid mill were observed.

The oil well cement used in grouting at the Boulder Canyon Project in 1943 had desirably long setting time with good early and ultimate strength.[20] Its cost, however, was $1.00 per bbl more than that of modified cement from the same mill.

It was felt that the addition of the correct admixture to the modified cement might impart the desirable properties of the oil well cement at nominal cost. An investigation was made in the Denver laboratory of a compound containing 87-1/2 per cent calcium lignosulfonate and 12-1/2 per cent triethanolamine. An oil well cement was used as a control and the additive was used experimentally with modified cement from the same mill as the oil well cement. The effect of the additive on slurry made with high-early-strength cement was also determined.

It was found that by use of 0.10 to 0.16 per cent by weight of the cement the desirable properties of the oil well cement were imparted to the modified cement. The admixture was prepared as a solution and added as the grout was mixed. The added cost for the admixture was about 7¢ per bbl. Viscosity was decreased, setting time increased, and strength unimpaired. The material was successfully used in the field.

The results with high-early-strength cement did not accord with those with the modified cement. With high-early the admixture caused premature stiffening and increased viscosity.

A rather extensive series of tests[17] involving small batches of grout were made and tested under several conditions for effect on consistency. Consistency was measured by use of the torque meter.

Two mixers were used. One was a small drink mixer, the other was similar to it but more vigorous in action. The effects of mixing time, addition of sand, all of which was finer than the No. 30 sieve, fly ash, several admixtures, special so-called low-solubility cement, and temperature, were observed. Voluminous tables of data were derived.

Briefly, it was found that fluidity increased with mixing time. Maximum fluidity was obtained after 10 minutes of mixing with the less vigorous mixer and in 5 minutes with the more vigorous mixer. Increasing water content decreased viscosity. The addition of sand without addition of water decreased fluidity. Increase in temperature decreased fluidity for grouts with low water-cement + filler (fly ash) ratios; however, at ratios of 0.65 by weight or more consistency was little affected. The effect of fly ash filler was to markedly decrease consistency at a constant water to cement + filler ratio as the amount of filler to cement increased. After one hour mixing grout with 80 per cent fly ash 20 per cent cement was about twice as fluid as grout with 100 per cent cement. The admixtures containing lignin compounds appeared to decrease consistency. The "low-solubility" cement was supposed to behave in grout without fly ash filler as other cements would with fly ash. At equal water contents ordinary cement plus fly ash provided grout of lower viscosity than did the special cement.

Another investigati [21,22] beyond that previously described[20] was made to find an admixture that when added to modified cement would retard its set without impairing its strength thus making it behave similarly to a good oil well cement. Such materials would be of value in tempering grout to be used in areas where hot water is encountered and in circumstances where it might be desirable to prolong the setting time.

Twenty-two admixture materials or combinations of materials in several different proportions were tested for their effect on nominal consistency and setting time of paste, strength of mortar cubes and viscosity of cement slurry containing 40 per cent water.

The most effective and economical materials for the purpose of retardation without loss of strength were lignin compounds. Used judiciously they appeared to impart to modified cement the qualities and characteristics of a finely ground oil well cement. Set was definitely prolonged, viscosity decreased, and they retained their retarding action under the conditions of test up to 140 F.

Further tests were made[23] at the Bureau Laboratory to determine the effects on grouting slurry of adding the admixture composed of calcium lignosulfonate plus triethanolamine and calcium lignosulfonate alone to one normal cement (type I), 10 modified cements (type II), five high-early-strength cements (type III), and one low-heat cement (type IV).

It was found that most of the modified cements responded very favorably to the addition of 0.16 to 0.30 per cent of the lignosulfonate-triethanolamine admixture. The low-heat cement responded favorably. The normal cement became flash setting with the combination admixture, but behaved well with calcium lignosulfonate alone. Only two of the five high-early-strength cements responded favorably to the combination admixture. All five responded favorably to calcium lignosulfonate alone, but not to as great an extent as the modified cements or the normal cement.

The investigation indicated that the combination of triethanolamine and calcium lignosulfonate should be tried in the laboratory to observe its effect on the cement selected for use in the field before actual trial on the job.

In order to determine if passage of cement grout through a suitable mill[24] would cause appreciable reduction in grain size of the cement thus resulting in a material which would better remain in suspension, and exhibit better flowability (penetration would be improved if grain size were reduced), tests were made with a "Charlotte" "colloid" mill.

The mill was borrowed from the Colorado School of Mines and tests were made with clearances between rotor and stator of 0.0030 to 0.0150 in. Slurries of ethanol and cement were used because in correct proportions they would produce slurries similar in characteristics to water and cement, but there would be no reaction between the ethanol and the cement. Cement suspensions of ethanol to cement (ml/g) of 0.40 and 0.60 were passed through the mill at various settings, dried and the change in fineness of the cement determined by the Wagner turbidimeter.

It was found that the maximum change in fineness with passage through the mill was about 8 per cent increase in specific surface. Actual grinding was negligible because the closest setting was 0.030 in. (76 microns) which would only grind material considerably larger than the 325-mesh sieve (44 microns). Most of the increase in fineness must have been due to dispersion. Subsequent passes of the slurry through the mill after the first pass were much less effective than the first pass.

Flowability was greatly improved and viscosity greatly decreased by passage through the mill. Curiously, the rate at which the solids settled from a column of slurry in a test tube was appreciably increased.

The effects of bentonite on the properties of neat grout were investigated[25] through a series of 35 experimental mixtures, in which 2 per cent bentonite by weight of the cement was added dry with the cement to the grout and premixed with water before adding to the grout. The effects on consistency, settlement, strength, and pumpability were determined.

It was found that bentonite thickened the grout at the same water content, but the thickening was not considered objectionable at water-cement ratios of 1:1 to 3:1. Bentonite increased the yield, that is it markedly decreased the amount the solids in the grout settled on standing. At equal consistencies bentonite produced a marked reduction in strength. The maximum thickening effect was obtained when the bentonite and water were premixed. The lime and alkalies leached from the cement were believed to inhibit complete swelling of the bentonite.

Data are reported on 104 mixtures[26] on which tests were made to determine the effects on fluidity, strength, and settlement, of using retarders, dispersing agents, and fillers such as fly ash, pumicite, and bentonite, and various combinations of admixtures and fillers.

Most of the grouts had a water to solids ratio of 1.57 by absolute volume. The mixtures were pumped through 250 ft of 1/2-in. pipe with gages along the pipe and the time required to discharge 1/2 cu ft of grout from the end of the line was observed. The same pressure was maintained at the pump for all grouts.

It was observed that the values for the coefficient of velocity obtained from the pumpability data did not agree with those obtained with a standard viscosimeter. It is believed that slurries do not behave as true fluids, but rather as true plastics. A study of the paper by Harold E. Babbit and David H. Caldwell, "Laminar Flow of Sludges in Pipe with Special Reference to Sewage Sludge," University of Illinois Experiment Station, Bulletin Series No. 319, November 1939, treats this phenomenon fully and leads to the belief that the Stormer viscosimeter can be used to accurately predict pumpability of neat grouts.

The investigation revealed that thick grouts were made less viscous by some dispersing agents and by the substitution of up to 30 per cent fly ash for cement without detrimental effect on strength. The substitution of pumicite, diatomaceous earth and bentonite for cement increased the thickness and decreased the pumpability of the grout. The dispersing agents containing accelerators while causing increased rate of strength gain caused rapid thickening of grout with some cements.

In discussing a paper by Simonds[27] on contraction-joint grouting of large dams, Simonds and Price[28] described Bureau of Reclamation tests which were made to determine the minimum joint opening that can be grouted and the efficiency of grouted joints in transmitting stresses. Although the tests were made to obtain information needed in grouting contraction joints, the results are also useful in the grouting of small openings in foundations. The tests showed that it is possible to grout effectively a joint having a width of 0.005 in. using cement screened through a 200-mesh sieve. Complete coverage of the joint area was not always obtained with this small opening, and pressures as high as 500 psi were required to force 0.75 water-cement ratio grout through the joint. It was indicated that an opening of about 0.008-in. width is the minimum that can be effectively grouted with cement grout passing a 200-mesh sieve.

Waterways Experiment Station

Grouting of foundation sands

The results of a study performed by the Soils Division, Waterways Experiment Station, to investigate the feasibility of grouting foundation sands using modifications of existing grouting procedures, with particular reference to cement grouts, and to consider the potentialities of grouts with new materials, were reported[29] in June 1955. The investigation consisted of two parts:

1. A review of published information on injection grouting theory and application, and factors affecting the success of grouting.
2. A laboratory investigation program, guided by these findings, to determine the potentialities of commercial type III portland cement (high-early-strength), scalped type III portland cement, slag cement, ground slag, and calcium acrylate grouts in grouting foundation sands; to explore the possibilities of improving these grouting agents through modification of the injection process or technique; and to develop a tentative criterion for predicting the success or lack of success that will attend the grouting of a particular sand with a certain grout.

Several references were listed in the report but only a few were discussed fully in the literature review. The more relevant and important points in the discussions are as follows:

1. Kollbrunner[30] stated that injection of cement suspensions is possible only at a pore-size diameter larger than 0.1 mm, and the lower limit of grain size for sands subject to grouting with cement is 0.8 mm. The required coefficient of permeability for successful cement grouting of sand is about 1000×10^{-4} cm per sec. Kollbrunner also reported that an injection can be successful only if the pressure increases as the soil pores become filled to capacity with injection material, and if the deposited materials are compressed by filtering off the liquid carrier. For this reason, a pump should be employed instead of air pressure

in injection work and when refusal is reached, the pressure should be maintained for 40 to 50 minutes.

2. Machis[31] experimented with cement slurries and concluded that no amount of pressure will make a cement slurry pass through sands with grains finer than 0.59 mm. However, penetrations in the order of 3- or 4-grain diameters were obtained in sands with a grain size of 0.59 mm. Air pressure was used to perform the injection tests and best results were obtained when the pressure was applied rapidly.

3. Terzaghi[32] reported that fissures with widths less than about 0.1 mm cannot be grouted with portland-cement grouts. If the effective grain size (D_{10}) of a compacted sand is smaller than 1.4 mm or that of a loose sand is smaller than 0.5 mm, the grout merely displaces the material by lateral compression and the result of the grouting operation consists of compact, tree-shaped bodies of solidified cement separated from each other by layers of sand with unimpaired permeability.

Laboratory tests were conducted to determine the minimum grain size of sand that could be successfully grouted with the potential grouts under consideration, and to collect data that might aid in the determination of the groutability of sands and in the selection of suitable grouts. In order to effectively evaluate the materials in both phases of testing, the following laboratory steps were carried out, for each specimen, in the order given: (1) permeability determination before grouting, (2) grout injection, (3) moist curing, (4) permeability determination after grouting, and (5) unconfined compression test (when practicable). Five basic grout mixtures, in which the cement, sand (grain size), water-cement ratio, and admixture were varied, were tested. The following pertinent conclusions were developed from the test results:

1. Each of the following grouting materials will grout sands with grain size (D_{10}) and sand-grout ratios as indicated:

Grout	Sand Grain Size D_{10}, mm	Sand-Grout Ratio D_{15} Sand/D_{85} Grout
Scalped type III portland cement (<30 μ)	0.29	18
Commercial type III portland cement	0.59	24
Slag cement	0.67	19
Ground slag	0.31	21

2. The anticipated low cost of producing cement for field grouting makes scalped type III portland cement the most promising potential grouting agent studied.

3. A water-cement ratio of 2:1 is near optimum and may be expected to produce a grout of maximum penetration and stability.

4. Calcium lignosulfonate did not have a beneficial effect upon cement grouts.

5. Grouting with the cements tested is not possible when the sand-grout ratio (D_{15} size of sand/D_{85} size of grout) is below 11.

6. Grouting is possible when the sand-grout ratio is more than 24. Although additional tests will be required to more closely define the sand-grout ratio range of groutable material, it appears that a sand-grout ratio of 19 may represent the limiting sand-grout ratio.

Pumpability of sanded grouts

Kennedy and Polatty,[33] in 1955, reported the results of the first phase of a comprehensive study of sanded grouts. In this phase, pumpability tests were made of cement grouts that included chemicals and mineral fines. Laboratory- and field-type mixing and pumping equipment were used in determining the amount of natural sand passing a No. 16 sieve that can be added with certain chemical admixtures and finely ground mineral fillers to portland-cement grout without injuring its pumpability. This information was sought because it is frequently desirable, from an economic as well as a structural standpoint, to use a cheaper material than neat cement in grouting foundation cavities.

The pumping tests were made with cement, sand, and water in combination with various admixtures. The admixtures tested were a commercial fluidifying admixture, diatomite, methocellulose, bentonite, calcium chloride, calcium lignosulfonate, and sucrose. Other tests to determine the effects of prolonged pumping and mixing on sand-carrying capacity of grout containing an inert material substituted for cement were made with fly ash. Laboratory tests were made on small batches of cement-sand grout to determine the approximate water requirements and bleeding that might be expected with various ratios of cement-to-sand at a relatively constant consistency. The consistency of the grout was measured by means of a torque consistency meter and a Stormer viscosimeter. Compressive strength and time of set were determined on grout that had the longest pumpability record for each combination.

General conclusions based on the results of the tests were:

1. It is feasible to pump sanded grouts.
2. Two parts of ordinary concrete sand after passing through the

No. 16 sieve to one part of cement can be pumped without the aid of admixtures at normal temperature.

3. Bleeding did not correlate with pumpability.

4. Pumping technique was of utmost importance. Sudden application of pressure after interruption in pumping and before good flow was re-established resulted in obstruction in the lines.

5. The age of the grout (the length of time it had been mixed and pumped) had an effect on its pumpability; the older the grout, the more sand it could carry and still remain pumpable. Visually it appeared that the older the grout, the more unctuous and homogeneous it became and the better it pumped. However, the grout stiffened with age and required addition of water to maintain original consistency.

6. The temperature of grouts containing portland cement apparently influenced their sand-carrying capacity. The higher the temperature, the more sand they carried.

7. The grout fluidifying admixture and methocellulose increased the sand-carrying capacity of the grouts to a small extent, diatomite to a greater extent, and bentonite to a very great extent; however, the use of more than 10 per cent bentonite permitted incorporation of such a large amount of sand that practically no strength resulted.

8. The use of calcium chloride had little or no effect on the sand-carrying capacity of the grouts. Calcium chloride accelerated the set and had a beneficial effect on the early strength.

The influence of sand grading and addition of mineral fines on the pumpability of cement grout was investigated during the second phase of the sanded grout investigation program, and the results were reported by Polatty[34] in October 1955. The second phase also included two series of tests to determine the maximum amount of sand that could be pumped in a sand-cement grout using sands of six different gradations. In the first test series, five percentages of sand, from 0 to 25 per cent, passing the No. 100 sieve were studied; in the second series, a sand deficient in material passing the No. 100 sieve was used and the effect of adding increments of finely divided mineral fillers, such as diatomite, fly ash, pumicite, and loess, was determined. Mineral fillers were added in increments that varied up to an amount equaling the weight of the cement.

Test results indicated that an increase in the amount of sand passing the No. 100 sieve from 0 to 25 per cent permitted the ratio of sand to cement in pumpable grout to be increased from 2:1 to 3:1 by weight. However, the water-cement ratio with the added fines increased from 0.63 to 0.87 by weight, while the 28-day compressive strength dropped from 3505 psi to 2120 psi.

The following conclusions were developed from the results of tests performed during this phase of the investigation.

1. Ordinary concrete sand scalped over a No. 16 sieve can be successfully used for grouting purposes.
2. When the sand is deficient in material passing the No. 100 sieve (nominal 0%), grouts with a ratio of one part portland cement to two parts of sand can be successfully pumped without the use of an admixture.
3. When the sand is deficient in material passing the No. 100 sieve,

the addition of finely divided mineral admixtures increases the sand-carrying capacity of the grout.

4. Diatomite, the finest of the admixtures tested and lowest in specific gravity, was the most effective in increasing the amount of sand that can be used in a grout; loess, the coarsest and highest in specific gravity, was the least effective.

5. No correlation was apparent between the bleeding and the pumpability. The bleeding increased with the addition of fine sand and was reduced with the addition of diatomite. The addition of fly ash, pumicite, and loess did not appreciably affect the bleeding.

6. In each of the series of mixtures, the water unit requirement increased with addition of fine material to maintain a constant consistency and the relative cement content actually decreased, resulting in a decrease in the compressive strength of the grouts.

A third phase of the investigation, to determine the influence of grading and specific gravity of manufactured sands on pumpability of grouts, was reported by Polatty[35] in February 1957. In addition to determining the maximum amount of manufactured limestone and traprock sands that could be incorporated in a pumpable grout, an attempt was made to evaluate the mixing properties of a high-speed mixer.

The grouts used in the pumping tests of this phase consisted of the following combinations of materials:

1. Cement, water, and limestone sands of three gradings, nominal 0, 10, and 25 per cent finer than the No. 100 sieve size.

2. Cement, water, and limestone sand, none of which was finer than

the No. 100 sieve size, with the addition of approximately 11, 25, 43, 67, and 100 per cent of both fly ash and loess based on the weight of the cement.

3. The same combination of materials listed in 1 and 2 except that traprock sand was substituted for the limestone sand.

The tests of grout mixtures contain[illegible] limestone sand showed that (1) an increase in the amount of sand finer than the No. 100 sieve size resulted in a large increase in the sand-carrying capacity of the mixtures, and (2) when fly ash or loess were added to mixtures containing sand with [illegible]ly no material finer than the No. 100 sieve size, the sand-carrying c[illegible]ty of the grouts was increased.

The tests of grout mixtures containing traprock sand revealed that (1) an increase in the percentage of traprock sand finer than the No. 100 sieve size resulted in an increase in the total amount of sand that could be used in a pumpable grout, and (2) the addition of fly ash to the traprock sand with essentially no material finer than the No. 100 sieve size afforded results similar to those obtained in the limestone sand-fly ash tests.

Upon examination of the pumping test results, it was noted that the increase in sand-carrying capacity of grouts incorporating traprock was relatively small compared to that of the grouts made with limestone sand. In addition, traprock finer than the No. 100 sieve was not as effective in promoting pumpability as the limestone sand. It was found possible to pump 1.75 parts of both limestone and traprock sand to 1.0 part of cement by weight when the sand contained no material finer than the No. 100 sieve size, and 7 parts of limestone sand or 2.25 parts of traprock sand to 1.0 part cement when 25 per cent of either sand was finer than the No. 100 sieve size.

mixer was compared with grouts prepared in a paddle mixer.

It was found that the addition of fly ash or diatomite had about the same effect as the addition of cement or other equally fine material. It was found possible to pump three parts of sand to one part of cement if the grout also contained 11 per cent fly ash by weight of the cement. With the same amount of diatomite 4.5 parts of sand to 1 of cement could be pumped. With grout containing 1 part of cement and 1 part of fly ash, 7 parts of sand could be pumped. With the same amount of diatomite 12 parts of sand could be pumped.

The pumpability and other characteristics of grouts of similar ingredients and proportions were similar whether mixed by the high-speed or paddle mixer.

Pressure grouting of fine fissures

In October 1956, Cook and Kennedy[37] reported an investigation involving several tests and procedures for pressure grouting fine fissures. The purpose of the program was to obtain information on the degree to which the penetration of fine fissures by grout is influenced by surface texture of the seam, pumping pressure, water-cement ratio, chemical fluidifiers, and finely divided mineral additives. It was also desired to determine the effect of these factors on the quality of the hardened grout films.

The study was conducted in three stages:

1. The first stage furnished data on the lowest water-cement ratio grout that could be pumped through fissures of 0.01-, 0.02-, and 0.03-in. thickness at 100-psi pressure, using standard field equipment and methods and the following grout mixtures: (a) neat cement, (b) cement plus fly ash, (c) cement plus fly ash plus a grouting aid. A study of consistency, bleeding characteristics,

The following conclusions were derived from a study of the test data:

1. Sands manufactured from limestone and traprock can be successfully used in sanded grouts.
2. The specific gravity of the sands within the range tested had little or no effect on the pumping characteristics of the grout.
3. Both fly ash and loess were effective in promoting pumpability when used with sands deficient in material finer than the No. 100 sieve size.
4. The limestone fines used in these tests, although having somewhat lower specific surface values than fly ash or loess, were pound for pound more efficient in promoting pumpability than the fly ash or loess.
5. Traprock fines, being relatively coarse, were not as efficient as fly ash or loess and were much less efficient than limestone in increasing sand-carrying capacity.
6. Setting time of the grout appeared to be lengthened slightly by addition of fly ash and loess.
7. Compressive strength varied with water content but that of the mixtures containing fly ash was slightly higher at 28 days.
8. Bleeding was minor for all the mixtures.
9. The results of tests for the evaluation of the high-speed mixer were inconclusive.

A fourth phase of an investigation of sanded grouts was reported by Polatty[36] in October 1958. The pumpability of grout with limestone sand was investigated when additional fine material in the form of fly ash or diatomite was added to the mixture. The pumpability of grouts prepared in the high-speed and setting times of the various grouts was also made. After the grouting tests were completed, chemical and petrographic examinations of bleed water and solid residues from some of the high water-cement ratio grouts, and further bleeding tests were made.

2. The second stage provided information on grout penetration obtained at pumping pressures of 25 and 50 psi using the three grout mixtures of the first stage and an additional mixture containing cement plus the grouting aid. Tests were also made of neat-cement grout plus calcium lignosulfonate pumped at 25, 50, and 100 psi, and of neat-cement grout plus a grouting aid pumped at 100 psi.
3. The third stage consisted of pumping tests (through a 0.03-in. crack) at 50 psi of the following seven grouts: (a) neat cement, (b) cement plus fly ash, (c) cement plus calcium lignosulfonate, (d) cement plus fly ash plus calcium lignosulfonate, (e) cement plus slag, (f) cement plus pumicite, and (g) cement plus calcined opaline shale. Stage three also included tests for consistency, bleeding, setting time, quality, and the solubility in distilled water of hardened grout films.

Ninety-seven pumping tests were conducted. The following conclusions were based on the data derived from the tests:

1. The surface texture of a fissure has a distinct influence on the thickness of grout that can be used to fill it. The smoother the surface the lower the water-cement ratio can be of grout that will penetrate the fissure.
2. The maximum grain size of the solids in the grout determines the minimum width of fissure that can be grouted. The ratio of fissure

width to grain size should probably be three or more.

3. The use of such materials as the grouting aid or calcium lignosulfonate increases the fluidity of grouts to some extent, thereby promoting penetration of a given crack with grouts of a slightly lower water-cement ratio than could be used successfully without them. Bleeding can be reduced somewhat and setting time increased by use of these materials.

4. It is impracticable to squeeze the excess water from a thin grout so as to leave a dense, hard filler in the cavity, at the pressures used in this program.

5. Bleeding largely prevents bonding of the grouting material to the upper surface of the fissure.

6. The use of finely ground mineral admixtures such as granulated blast-furnace slag, pumicite, and opaline shale can reduce the bleeding of a grout and greatly improve the continuity and appearance of the hardened grout film.

7. The solubility of a grout film is influenced by the water-cement ratio and composition of the film, and length of curing. Certain mineral admixtures can be used to reduce the amount of leaching that a grout film undergoes.

8. A straight-line pressure gradient occurs along a fissure being grouted only if the fissure is of sufficient width.

9. Neat-cement grout with a water-cement ratio of 0.43 penetrated the 0.03 in. wide fissure at 25 psi, but it was necessary to increase the water-cement ratio to 2.67 before neat grout would penetrate the 0.01 in. wide fissure at the same pressure.

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